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C3D2 – AN IMAGING PAYLOAD ON ALSAT-NANO

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ABSTRACT

An experimental CubeSat camera system using 3 separate CMOS imagers was flown in 2014 on UKube-1. In response to an announcement of opportunity in December 2014, we proposed an upgrade to our C3D imager payload, which was accepted to fly on AlSat Nano. Launched in September 2016 the system has been operational for over 1 year and has returned both images and housekeeping data, including detailed temperature and radiation dosimetry measurements. Through these in-orbit demonstrations on CubeSats, the image sensors and payload have attained TRL9, and these are now being used in other flight opportunities. In this paper we describe the C3D imager payload, which comprises 3 independent CMOS image sensors used in different camera systems; two wide field cameras are specifically optimised with one to observe the Earth from the 650km orbit, and the other with its focus set to 40cm to observe a deployable boom from the CubeSat. The third camera system is fed by a miniature Cassegrain telescope with a narrow field of view. The experiment controller also contained thermometry and two RADFET dosimeters, one located on the payload, with the other deployed at a different point on the spacecraft.

In this paper we will describe the experiment design and operational performance, and review the in-orbit data obtained during the operations covering over 17 months in-orbit, in addition to discussing lessons learned from the flight experience. We also discuss further developments of the payload concept which we are currently working on toward future flight opportunities.

1 INTRODUCTION AND OBJECTIVES

Teledyne e2v are established suppliers of CCD technology into spacecraft (such as XMM, Gaia, Hubble, MarsExpress etc.). However in the future, their newer CMOS image sensors will begin to take a much greater market share for visible space imaging. The primary goal of C3D2 and its

precursor C3D, was to provide an in-orbit demonstration (IOD) for this new CMOS imaging technology. In response to a call from the UKSA for payload concepts for a joint CubeSat between the UK and Algeria, called AlSat-Nano, we proposed an imaging payload which would demonstrate e2v's new CMOS integrated imaging sensors which will:

- be a technology demonstrator for use of the new range of CMOS imaging technology being developed by e2v for other mission opportunities, such as the JANUS camera on JUICE, Solar-C, lunar and Martian rovers, and for future Earth observation instruments etc.
- to increase the TRL of the technology
- to demonstrate the technology for future missions and attract inward investment from other programmes to develop the technology further
- take images of the Earth
- to provide housekeeping of payload operating temperatures and total ionising dose (TID).

The project builds upon the earlier instrument, C3D, which was flown on UKube-1 in 2014 [1]. The imager is based upon Te2v's 1.3 Mpixel "camera on a chip" CMOS image sensor, referred to as "Sapphires" [2]. Technology development and readiness is already advanced: radiation hardness and space applications have been investigated through PhD studentships [3]. The device technology has been demonstrated to withstand 10^{10} protons.cm⁻², a TID of 200 krads and has been recently tested using heavy ions for SEU/SEL effects and has been demonstrated to work without any catastrophic burnout effects.

We call the payloads C3D – a Compact CMOS Camera Demonstrator, which of-significance includes 3 CMOS image sensors, each performing different functions; wide and narrow field imaging, plus radiation damage assessment, with C3D2 being the 2nd flight opportunity. The instrument also contains thermometry and dosimetry monitoring functions to enable the results obtained to be correlated with those obtained in laboratory testing on the ground. The following sections describe the rationale behind the instrument, the CMOS image sensors, and the C3D payload in greater detail.

2 TELEDYNE e2v CMOS IMAGE SENSOR

2.1 Sensor Description

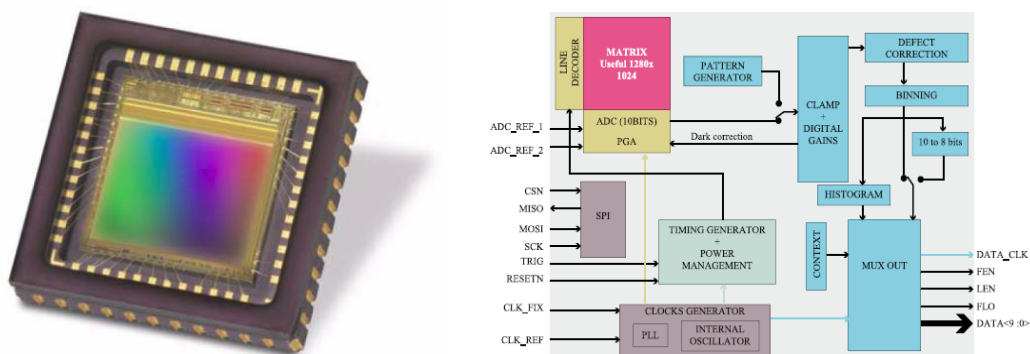


Figure 1: The 1.3 Mpix CMOS "Sapphires" sensor used in the instrument (left) and the system architecture (right). This highly integrated sub-system makes the creation of a space imager with much lower mass/power/volume requirements than using more conventional CCDs

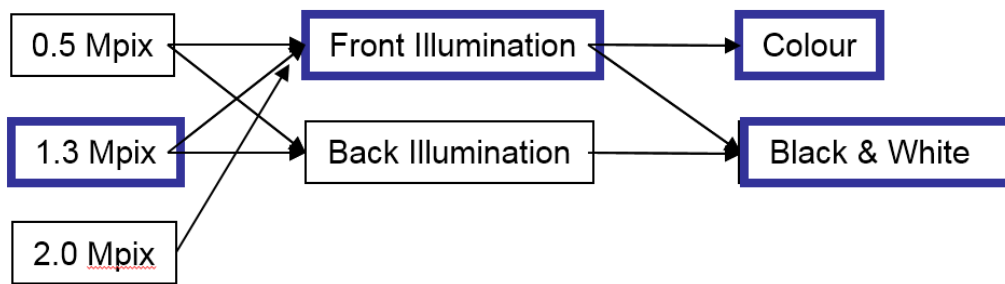


Figure 2: Imager options available for the instrument at the time of the proposal, and in blue the baseline options chosen

Teledyne e2v is a world-leading provider of CCD-based scientific imaging sensors into the global space community, specialising in high performance sensors, customised to the application needs, often with back-illumination to improve sensitivity. This tailored service to provide customised sensors is now extending to the provision of application-specific CMOS imaging technology. In this instrument we use one of the new “Eye-on-Si” CMOS imagers [2]. This instrument is undoubtedly *not* the first flight of a CMOS imager on a CubeSat, however the other imagers have been very simple COTS components. The **unique** aspect of this instrument is that we aim to fly one CMOS imager of a family whose design heritage will provide traceability from our existing space radiation damage qualification campaign, through to future space imagers coming from the Te2v CMOS design stable.

Several variants exist of the proposed COTS CMOS imager represented schematically in Figure 2. For the instrument design we chose the 1.3 Mpixel imager and for C3D2 used both its colour and B&W variants. This concept builds upon the CMOS imager developments and space radiation damage effects which are two key research themes of the CEI. We have been involved with e2v’s CMOS imager developments since its humble beginnings in 2005 through UK CASE PhD studentships, and currently have 4 PhD students performing research into CMOS imagers exploring both their design and use, and radiation hardness for use in space.

3 C3D2 PAYLOAD CONCEPT

The instrument, designated the Compact CMOS Camera Demonstrator (C3D) was conceived as a technology demonstrator, both demonstrating the imaging technology, and by designing a complex payload, to demonstrate some of the capabilities of the CubeSat platform.

3.1 Instrument Technical and Scientific Objectives

The instrument objectives are listed below:

- be a technology demonstrator for use of the technology on other mission opportunities, such as the JUICE imager, Solar-C, lunar and Martian rovers, and for EOS etc.
- monitor the imager performance as the radiation damage increases (for both ionising dose and displacement damage) and to correlate this to laboratory measurements
- to monitor the instrument temperature over complete orbits using housekeeping mode
- to provide accurate TID dosimetry at the instrument (and hence spacecraft) using RADFETs
- take high quality images of the Earth which can be used for outreach, schools, and showcase the CubeSat as an imaging platform

- Contribute to the training and research of PhD students and early career PDRAs

3.2 Imaging of Earth and Deployables

One of the goals of the payload was to take images of the Earth using the CubeSat platform, however in addition, the AlSat Nano CubeSat was going to demonstrate new deployable boom technology from Oxford Space Systems Ltd (OSS) in the UK [4]. Developing from the C3D instrument on UKube-1, we decided to provide three imaging systems on the payload; one wide field imager has a standard camera lens with $\sim 40^\circ$ FOV, designated the Wide Field Imager (WFI) with a colour sensor focussed on the earth, a second WFI with optimum focus at 45cm using a B&W sensor for monitoring the deployable boom on-orbit, called the “Boom imager”, and the third system having a colour sensor with an experimental Cassegrain Telescope configuration with focal length ~ 150 mm,

Using a standard lens from Sunex with 40° FOV, the spatial resolution is ~ 350 m from 650 km altitude with a swath width of ~ 450 km. Using the on-chip global shutter option, the image exposure may be programmable from a few μ s to several seconds with a typical exposure of the sunlit Earth being ~ 1 ms; equivalent to 7 m motion over the earth. This will freeze any image blur due to the motion of the spacecraft when using such an optical arrangement.

4 SYSTEM OVERVIEW

The C3D2 instrument uses the standard CubeSat PC104 experiment slot with a $9 \times 9 \times 2 \text{ cm}^3$ volume. The payload has several novel attributes. For the imaging, it possesses three CMOS image sensors. The WFI and Boom imagers provide wide field imaging with an $\sim 40^\circ$ FOV. The NFI has its own CMOS sensor and has an $\sim 2^\circ$ FOV. The locations of the co-aligned NFI, WFI and Boom imagers were constrained by the slots available in the CubeSat support structure. The experiment is complemented by inclusion of two RADFET dosimeters, each with their own PT100 temperature sensors. One RADFET is located on the experiment support system (ESS) PCB to provide an estimate of the TID received by the experiment. The other RADFET and PT100 is provided on a flying lead to the spacecraft to monitor other critical areas. In this instance the second monitoring position is by the spacecraft batteries.

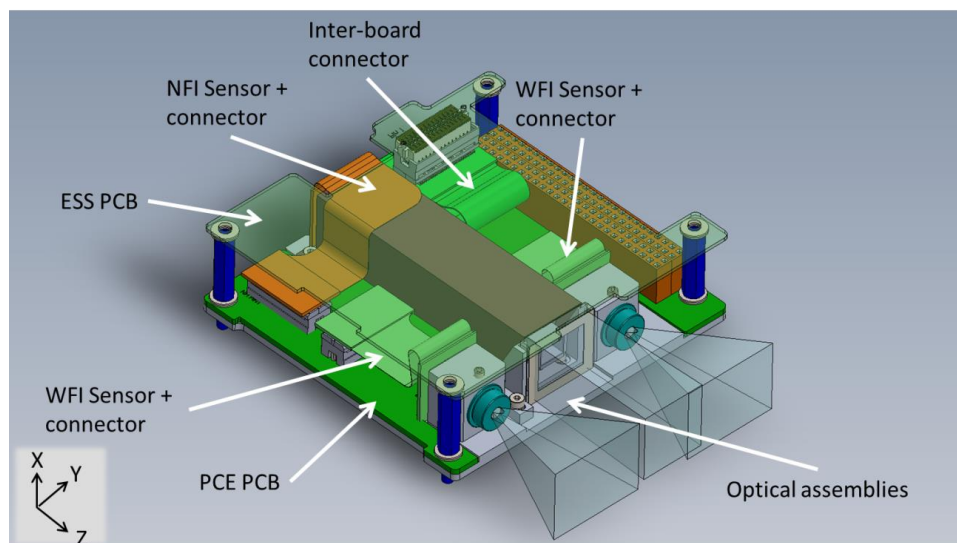


Figure 3: Isometric CAD model of the C3D instrument showing the location of the main parts

Figure 4 gives an overview of the system functional blocks of the experiment and how it interfaces to the spacecraft. The two PCBs of the instrument can be seen; the Payload Control Electronics (PCE), and the Experiment Support System (ESS), in addition to the 3 CMOS image sensors which are controlled by the FPGA on the PCE. The CMOS image sensors are configured as separate modules on flex-rigid PCB assemblies, which enable them to be placed in different positions using minor modifications to the flex design. The C3D2 flexies are between 2-5cm in length, however, in developments subsequent to the launch of AlSat Nano, the WFI CMOS imager has been demonstrated on an extended flex-rigid PCB of length up to 25 cm; thereby enabling imagers to be placed on any of the faces of e.g. a 6U CubeSat.

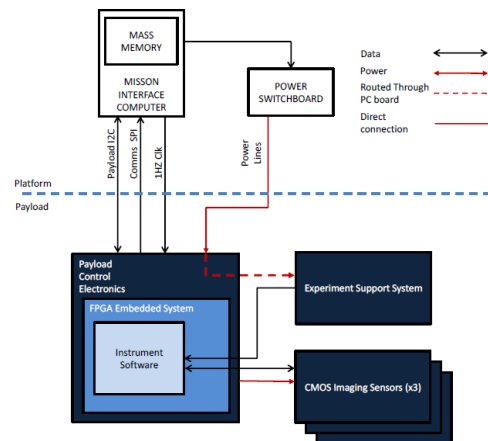


Figure 4: Main components of the C3D instrument showing the payload control electronics (PCE) which drives the 3 CMOS sensors, and communicates with the experiment support system (ESS)

5 SUB-SYSTEM DETAILS

5.1 Payload Control Electronics - PCE

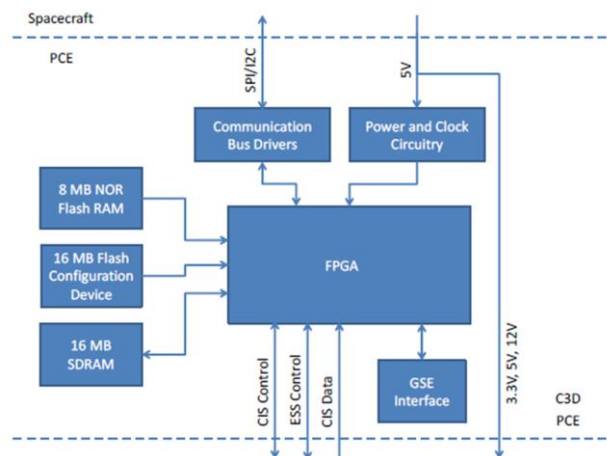


Figure 5: Functional blocks within the PCE

The PCE was designed and manufactured by XCAM Ltd. Figure 5 gives a schematic of the main functional blocks within the PCE, whilst Figure 6 provides photographs of the top and bottom of the PCB. The PCE was constructed as a 10-layer PCB, and although the build standard could use COTS components, the assembly used Pb-solder to help suppress tin-whiskers which might develop over the lifetime on-orbit. The irregular shape to the PCB arose due to the constraints introduced by

the mechanical structure of the instrument and the optical components. In particular, the experiment was built on an aluminium frame which was both used to support the optics and to provide a heatsink for the power dissipated.

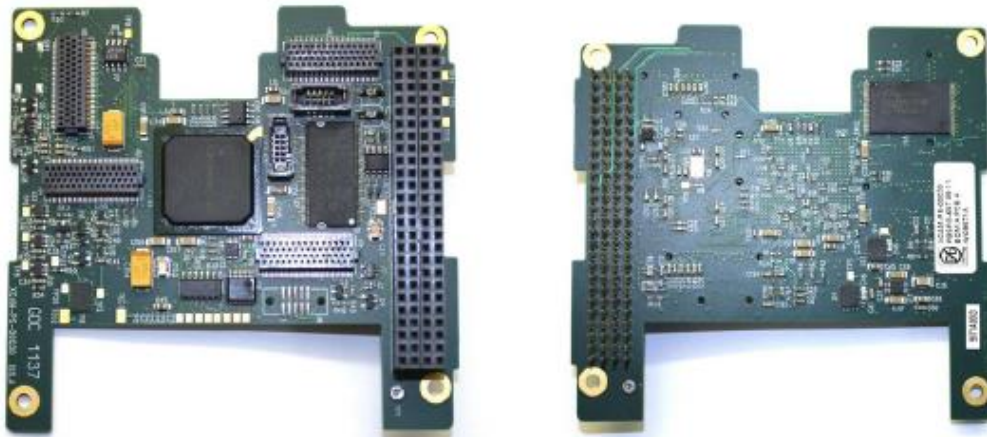


Figure 6: Photographs of the payload control electronics which were developed by XCAM

5.2 Experiment Support System - ESS

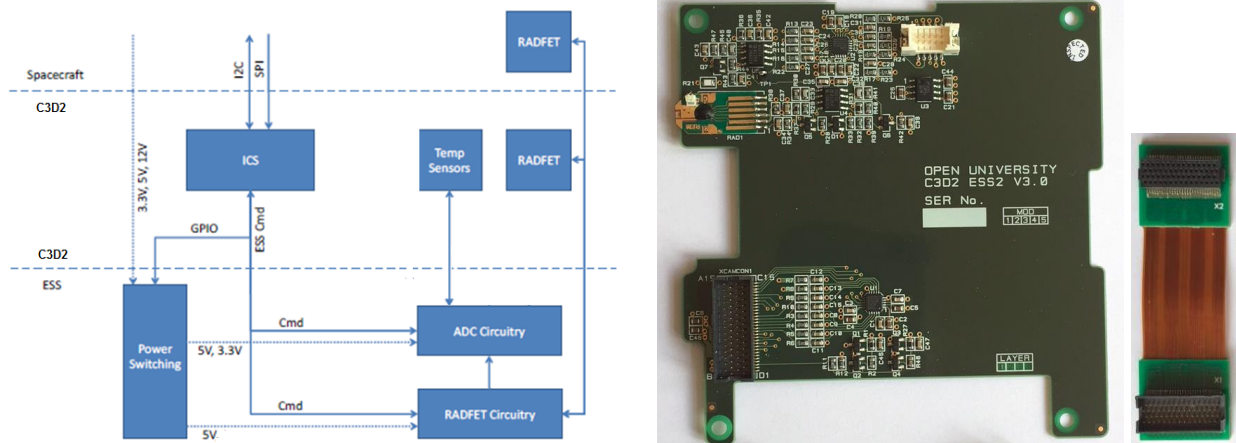


Figure 7: Functional blocks within the Experiment Support System (left) and photograph of the assembled PCB and the PCE-ESS inter-board flex-rigid connector (right)

The ESS was designed and manufactured at the Open University. Figure 7 (left) provides a schematic of the main functional blocks of the ESS (lower half) and the connections to the RADFETs and PT100 temperature sensors. Figure 7 (right) provides photographs of the ESS PCB together with the flex-rigid assembly which connects the ESS to the PCE. The RADFET for monitoring the experiment TID can be seen in the top left tab of the ESS photograph. Again, the PCB cut-outs were to accommodate the optics and the PC104 connector carrying the spacecraft bus.

Figure 8 shows the design of the Cassegrain telescope forming the NFI. This is a 2-mirror configuration taken from C3D on UKube-1, with M1 formed by precision diamond turning, whilst M2 is formed as a reflecting zone on the main entrance window. The M1 and M2 are silver-coated for increased reflectivity and performance against tarnishing. The entrance window is a double-sides AR coated optical glass substrate. The assembly has a number of baffles to reduce the stray

light. The overall configuration results in an aperture of $\sim 1 \text{ cm}^2$ with a focal length of 145 mm. The CMOS image sensor is bonded to the rear of the M1 behind the central hole in the mirror.

5.3 Narrow Field Imager

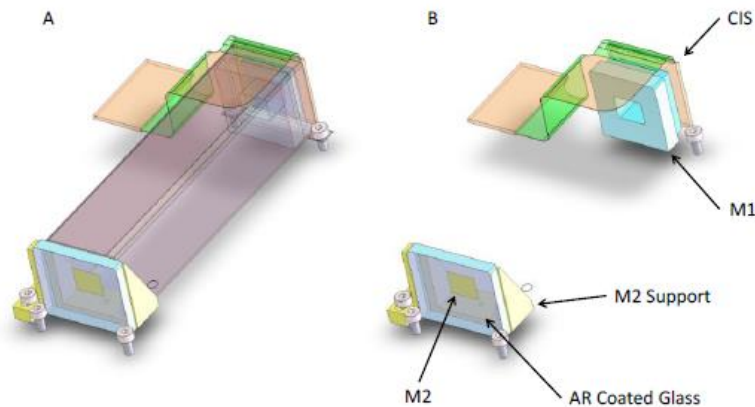


Figure 8: Detail of the NFI telescope design showing a) the full construction

5.4 Dosimetry

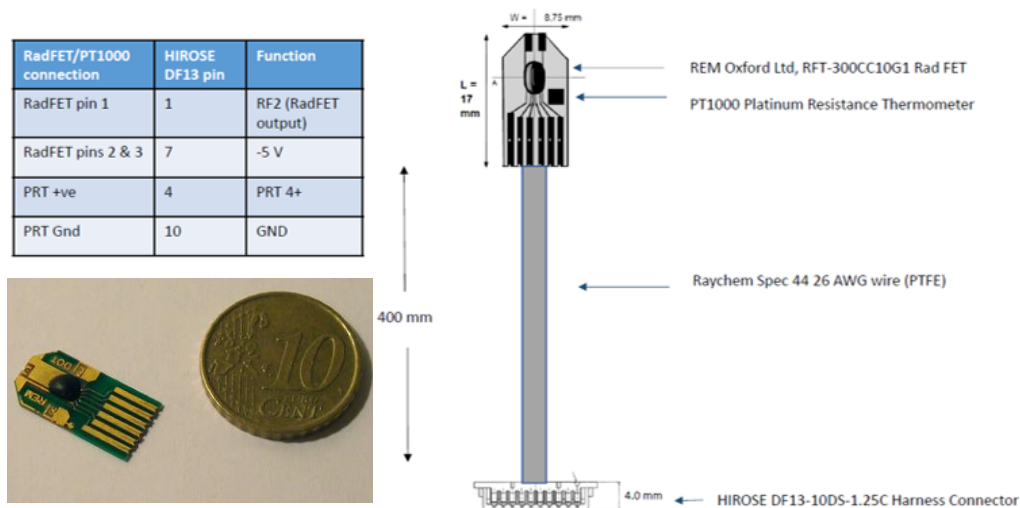


Figure 9: Detail of the remote RADFET and temperature sensor to be placed elsewhere on the spacecraft

Figure 9 shows the detail for the 2nd RADFET system which is used for both temperature and dosimetry measurements at a remote location on the spacecraft. In the case of AISat Nano, the 2nd RADFET was located close to the

5.5 Mass, Power and Data Budgets

The instrument mass, power and data volumes are given in Tables 1-3 below. The electronics has standby mode, imaging and housekeeping (when temperature and RADFETS are read), and each of these modes has slightly different power consumptions. In addition, due to the telemetry budget for the CubeSat, the transfer of a full resolution image, with compression, may take between 2-4 days. Because of this limitation, the PCE also creates thumbnail images of reduced size. These thumbnails can be downloaded in a single pass over the ground station to enable a decision to be made on which images to download and which, if any, to discard. The very low duty cycle imposed on the instrument due to the telemetry bandwidth implies that the orbit-averaged power is therefore

be very low, in the few mW regime.

Table 1: Power Budgets

Power (mW)			
	Mean	Peak	Maturity
Standby	880	950	Measured
Imaging	885	900	Measured

Table 2: Data Volumes

Image Data Volumes	
1 Image (raw)	1.3 MBytes
Image with compression	100-650 kBytes
Thumbnail	12 kBytes

Table 3 gives the design mass breakdown of the instrument for the various component parts, together with mass margins. The main contributors to the mass of the instrument are the metal framework and the various connectors themselves. The measured mass of the final flight unit was 175g including all fixings, adhesives and mounting framework.

Table 3: Mass Breakdown

Item	Mass (g)	Margin
Metalwork	62	20%
Connectors	40	10%
Fixings	5	20%
PCBs	21	20%
CMOS Imagers	2	5%
Lens+Mirrors	15	10%
Total	145 g	(175 g inc.)

Table 4: Operating modes for C3D

Mode_ID	Name	Description
0x00	WAKE UP / STANDBY	Initial systems check, standby mode
0x01	IMAGING	Sets up the payload into image capture mode. Images can be captured from any 3 of the sensors.
0x02	HOUSEKEEPING	Grab all housekeeping data
0x05	USER	Executes user defined code

FLIGHT MODEL ASSEMBLY & TESTING Figure 10 gives photographs for the FM instrument assembly (left) and its location on the whole spacecraft (right). The instrument Boom imager, NFI and WFI can be seen. The colour WFI imager also had a UV cut-off filter at 420nm to avoid glare from the Earth albedo. The instrument was also shipped including a flying lead which would have enabled last-minute re-programming of the FPGA. In the end, this was not used, and was cut and secured prior to sealing the spacecraft. The C3D2 payload was at the far end of the 3U assembly, and was located just above the deployable boom payload provided by OSS.

Figure 11 gives images from pre-launch testing of a standard test chart (left) and (right) of a spare EM unit from an airplane window to ensure the automatic exposure routine was working correctly. Figure 12 gives the test results during the focusing of the boom imager, where the focus was set to 45 cm to capture detailed images of the deployed boom.

The payload was delivered to Surrey Space Centre for integration in December 2015, and was successfully launched by PSLV (India) on 26th September 2016 into a polar orbit with 670 km altitude.

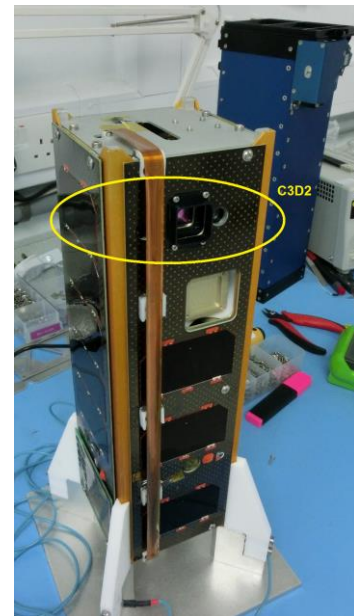


Figure 10: Assembled FM of C3D2 (left) and integrated onto the 3U CubeSat Ain the lab (right)

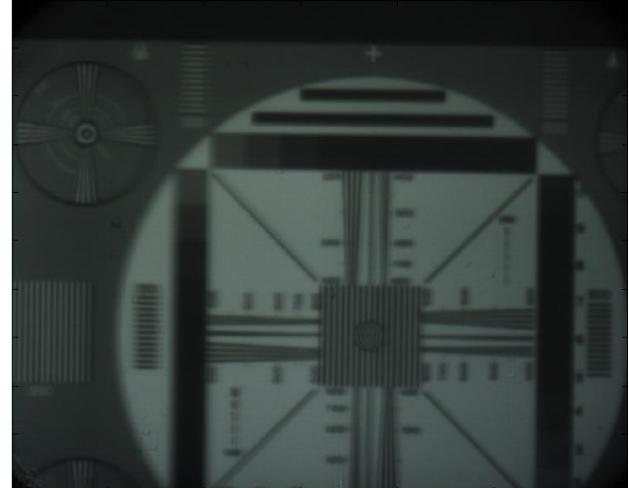
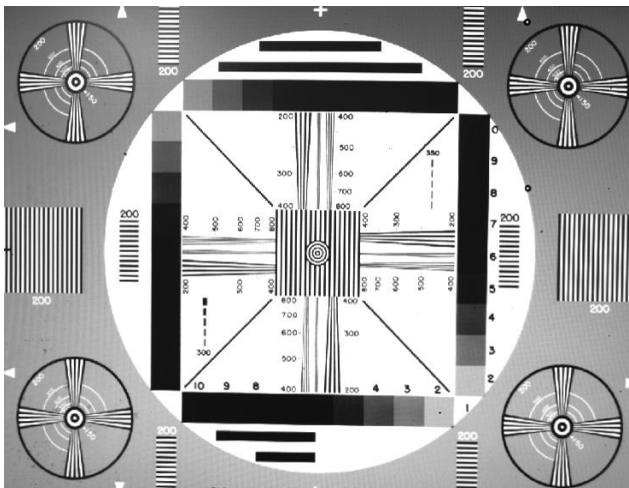


Figure 11: Images taken in the cleanroom of a standard test pattern printed on A4 sheet using the WFI at a distance of 40cm (left), and the NFI at a distance of 4m a standard test chart in the laboratory (right)

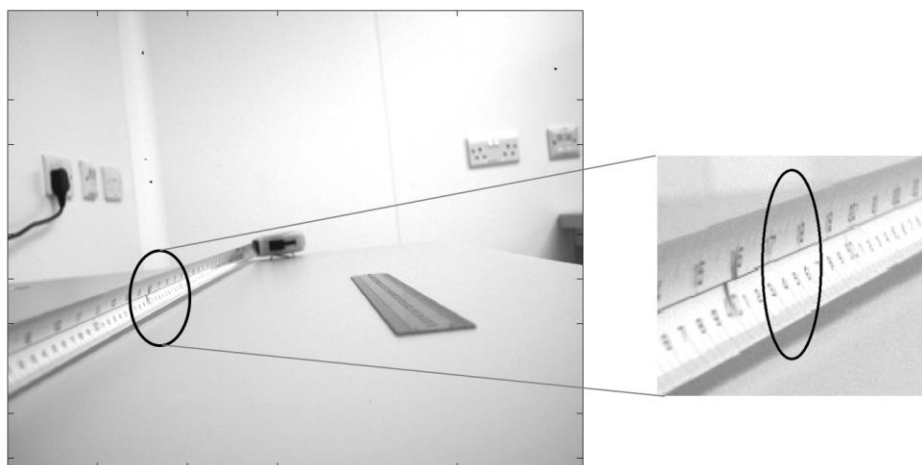


Figure 12: Laboratory testing in the cleanroom of the B&W boom imager to set the focus to ~45 cm



Figure 13: Image taken using a spare EM unit with the WFI during a “test flight” on an airplane above clouds to verify operation of the automatic exposure for an illumination level similar to that in-orbit

6 IN-ORBIT RESULTS

Since launch we have received many datasets ranging from housekeeping (>100), thumbnails (>50) and high resolution images (>30). This section describes just a few of the results obtained. In Figure 14 we show one of the low resolution thumbnails (left) consisting of 120x100 pixels. The thumbnail is comprised of selecting 1-in-10 pixels in x and y, in this instance selecting blue pixels so the thumbnail can only represent a B&W image, and results in a data file having only 12 kB. This small thumbnail datafile can then be downloaded during a single pass of the spacecraft over a ground station, and a decision made whether to commit the time required to download the whole image. At the early part of the mission, full high resolution image download took between 3-4 days depending upon ground station coverage and error checking. However at the current time, after some modifications to the CubeSat architecture, download of a full image can be obtained in just one day. The image on the right of Figure 14 gives the full-colour RGB image associated with the thumbnail; in this instance of a view of the Earth’s limb, and with the boom partly deployed, and out of focus at the bottom.

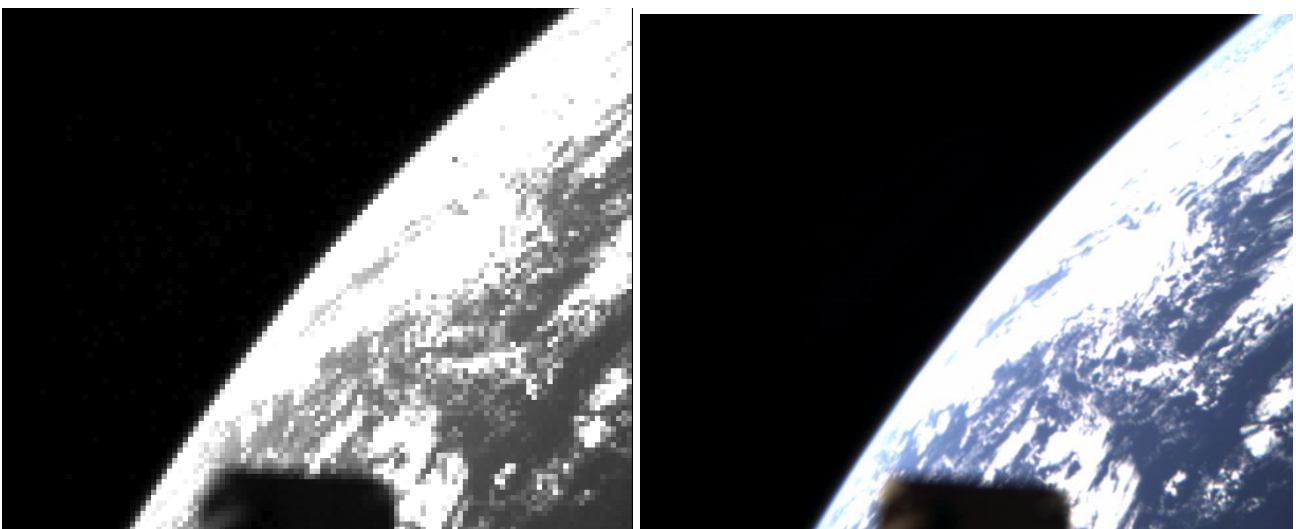


Figure 14: WFI thumbnail having 120x100 pixels (left) and the full colour image with 1280x1024 pixels (right)

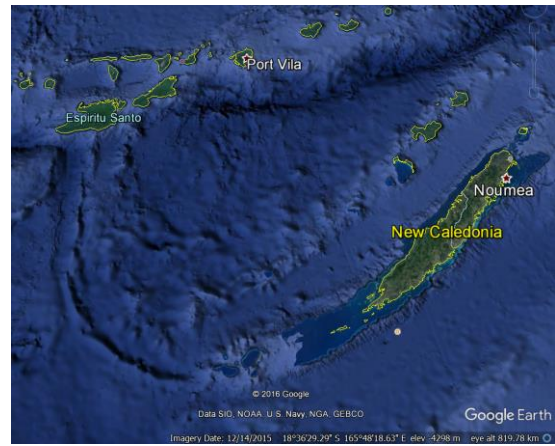
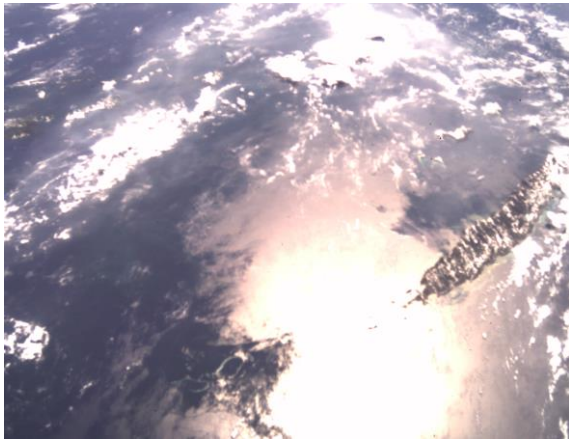


Figure 15: WFI image taken over New Caledonia compared to the map from Google Earth

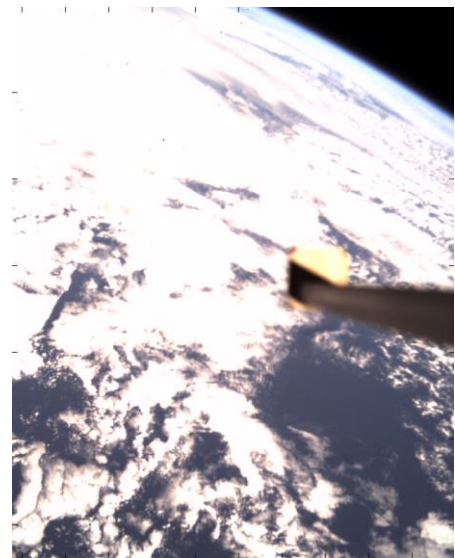


Figure 16: First WFI image taken over Archangel with boom deployed in December 2016 (left) and another image showing the Earth limb over the Atlantic off the east coast of the USA (right)

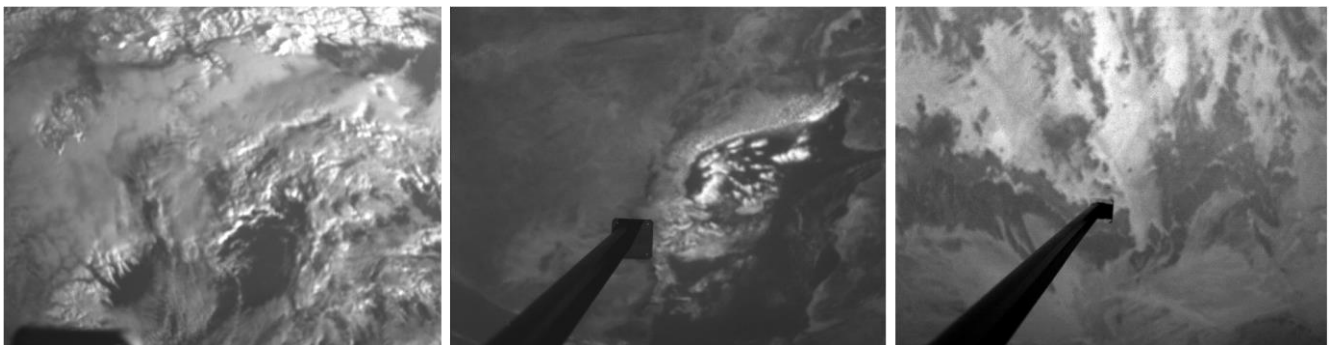


Figure 17: Three snaps from the Boom imager indicating the deployable boom at different extensions

Figure 15 gives another high-resolution RGB image taken over New Caledonia, and compared to the map of the same region from Google Earth. For many of the near-nadir pointing images, it was possible to overlay the C3D2 images with high accuracy over the Google Earth model, to within a few km across the image. Figure 16 gives other examples of images from the WFI, in this instance with the boom deployed and in the field of view.

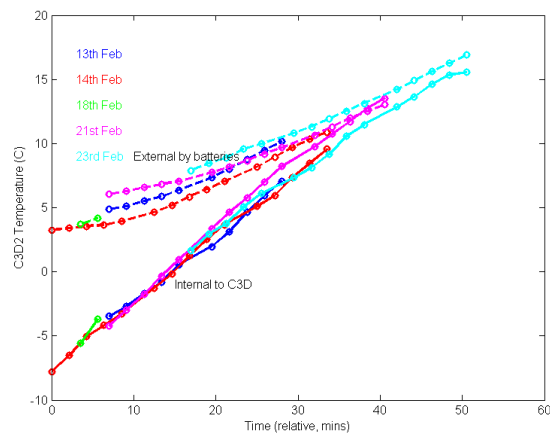


Figure 18: Temperature readings of both the C3D payload and the remote RADFET located by the batteries

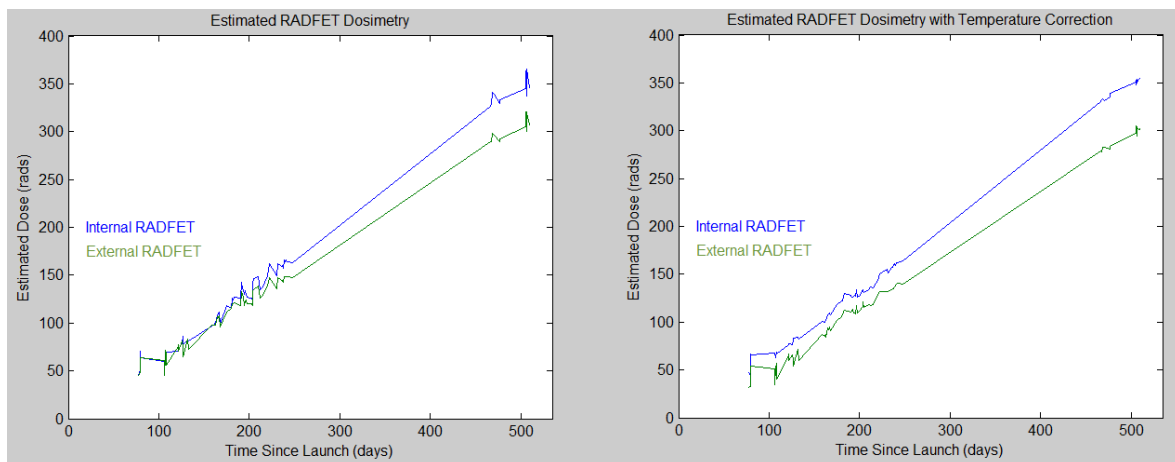


Figure 19: RADFET dosimetry readings over the duration of the mission derived from the drain-source voltage of the FET (left), and after correction for temperature effects (right)

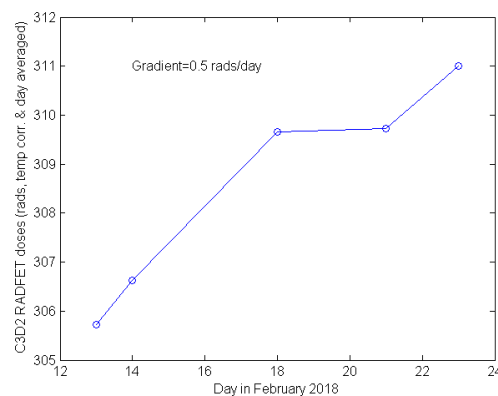


Figure 20: RADFET dosimetry readings taken over 10 days in February 2018 demonstrating an average accumulation of ~0.5 rads/day, and also indicating the technique having a dosimetric accuracy of ~0.5 rads

In February 2018 an experiment was performed to take housekeeping datasets repeated at 2 minute intervals. Figure 18 gives the analysed temperature readings for both the PRT on C3D2, and the remote RADFET located by the batteries. The temperature excursion experienced by C3D is significantly larger than that by the batteries, and from Figure 10 this might be expected, since the C3D payload is located at the end of the 3U spacecraft, whilst the batteries are more central. Overall we anticipate that over an orbit cycle the payload typically sees temperature excursions between

approximately -15°C to $+20^{\circ}\text{C}$, i.e. essentially the payload sits around zero degrees C.

The RADFETs were equipped with temperature monitoring to enable correction for measurement effects, and Figure 19 shows the estimated RADFET dosimetry based on the drain-source voltages (left). However on the right we re-interpret the data after correcting for temperature, showing a much smaller deviation in the readings. Overall we see that the payload appears to be experiencing an increase in TID of $\sim 200\text{--}250$ rads/yr, and again, the C3D internal RADFET is experiencing more dose than the RADFET located by the batteries, due to the local shielding.

Figure 20 gives averaged readings over several days where one can see that the dose rate is increasing by typically 0.5 rads/day, and that the dosimetric accuracy is at the ~ 0.5 rads level, when averaging several readings and correcting for temperatures.

7 SUMMARY AND FUTURE DEVELOPMENTS

We have described the rationale behind and design of a compact CMOS camera demonstrator for a CubeSat payload, the flight version of which is depicted in Figure 10 above. The instrument is comprised of an experiment controller with three separate CMOS image sensors which perform different functions; a wide field imager, a boom imager which monitors a deployable structure, and a narrow field imager. In addition, the payload performs radiation damage and temperature measurements using RADFETs and PRTs can measure temperatures and radiation doses at specific locations with an accuracy of 0.5 rads. Since the launch of C3D in 2014 and C3D2 in 2016, EM versions of the payload have been provided to other groups for experimentation, thereby extending the impact of the C3D developments. Whilst early CubeSats were particularly targeted at training opportunities and in-orbit-demonstration, an increasing number of applications are now being developed, some addressing quite challenging scientific applications and even new mission concepts. Since the flight of C3D2, the payload concept has continued to be developed, most notably for the payload controller on CASPA – a CubeSat to monitor Cold Atoms in space, ultimately for detecting local gravity variations over the Earth [5]. In addition, to support the growing mission opportunities, beyond the Te2v Sapphires 1.3Mpix sensor, experience has been gained using the 4 Mpix and 20 Mpix CMOS image sensors from CMOSIS, and work is currently progressing to develop a low-noise system to drive scientific CCDs using the same basic controller. With the C3D/C3D2 payloads we have therefore demonstrated successful operation of the Te2V Sapphires sensors, to TRL9, and have the basis for a payload controller which can support a variety of imaging systems in the future; ranging from low-noise scientific CCDs to COTS CMOS imagers, for both imaging in the visible, UV and X-ray bands, and deployment monitoring, by operating from a central payload controller and positioning several of the $\sim 1\text{cm}^3$ imaging camera systems anywhere on the 3-6U CubeSat.

8 ACKNOWLEDGEMENTS

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